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ORIGINAL REPORT

EFFECTS OF PUSH-OFF ABILITY AND HANDCYCLE TYPE ON HANDCYCLING PERFORMANCE IN ABLE-BODIED PARTICIPANTS

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Objective: **To assess the effects on handcycling performance and physiological responses, of: (*i*) making a closed chain by comparing handcycling in a recumbent bike with 2-feet footrest (closed chain) with handcycling with 1 footrest (partial closed chain) and without a footrest (no closed chain); (*ii*) equipment by comparing handcycling in a recumbent bike with a kneeling bike.**

Methods: **Ten able-bodied participants performed submaximal exercise and sprint tests, once in a kneeling bike and 3 times on a recumbent: 2-feet support, 1-foot support and without foot support. Physical strain (submaximal oxygen uptake and heart rate), peak (PO_{peak}) and mean power output (PO_{mean}) were measured.**

Results: **Significantly higher PO_{peak} and PO_{mean} were found with 2-feet support (mean 415 W (standard deviation (SD) 163) and mean 281 W (SD 96)) and higher POmean with 1-foot support (mean 279 W (SD 104)) compared with no foot support (mean 332 W (SD 127) and mean 254 W (SD 101)), $p<0.05$. No differences were found for physical strain. In the kneeling bike, PO_{peak} and PO_{mean} were significantly higher (mean 628 W (SD 231) and 391 W (SD 121)) than in the recumbent (mean 415 W (SD 163) and 281 W (SD 96)), $p=0.001$.**

Conclusion: **The ability to make a closed chain has a significant positive effect on handcycling sprint performance; therefore, this ability may be a discriminating factor. Sprint performance was significantly higher in kneeling compared with recumbent handcycling.**

Key words: (sub)maximal exercise; physical strain; power output; able-bodied; handbike.

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MAIN MESSAGE

A valid and clear classification system is essential to accomplish fair competition in handcycling. Sometimes athletes with different lower-limb abilities and, therefore, a different push-off ability, are grouped in the same class. In this study we investigated the effect of push-off ability during sprinting. It was concluded that the power output achieved with the push-off ability was significantly higher than without push-off ability. These findings should be taken into consideration in classification.

A valid and clear classification system is the key aspect to accomplishing fair play in para-sport (1). Classification is sport specific and serves to group athletes into sport classes based on the impact of their impairment on the specific sport (2). Each sport has its own classification system with a list of eligible impairments and Minimum Impairment Criteria for each impairment (2). This indicates which athletes are allowed to participate in that sport and groups athletes into sports classes while minimizing the impact of the impairment (2). The importance of the development of evidence-based systems of classification was already stated in the first International Paralympic Committee (IPC) Classification Code in 2007 (3). Despite influential studies on classification over the past years; for example, in wheelchair rugby (4), several classification systems are still based on expert opinion rather than evidence-based practice (5, 6).

In handcycling, 5 sport classes are distinguished: H1 is the class with the most impairment and H5 with the least. Among the eligible impairment types (7), most international handcycling athletes either have a spinal cord injury or lower limb amputation. The H1–H4 athletes ride in a recumbent (lying) position (Arm-Power (AP)-bike), whereas H5 athletes ride in a kneeling position (Arm-Trunk-Power (ATP)-bike) (Fig. 1) (7, 8). H4 athletes have no or very limited lower-limb function, whereas H5 athletes have incomplete loss of lower-limb function (7). If an athlete with incomplete loss of lower-limb function is not able to ride in an ATP-bike because of medical issues, such as severe scoliosis, the athlete will be allowed (as decided by a Classification Panel) to compete in the H4 class in an AP-bike. However, athletes with lower-limb function might theoretically have an advantage compared with

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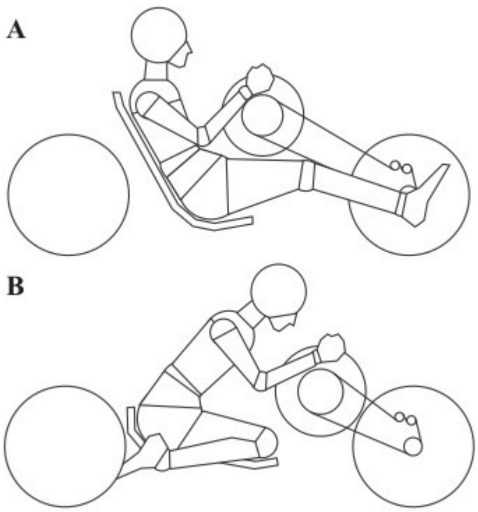

Fig. 1. (A) Arm-Power (AP)-bike. (B) Arm-Trunk-Power (ATP)-bike.

athletes without lower-limb function, as they might be able use the (partial) function of their legs to brace themselves in the bike, push off against the footrests and subsequently use this resistance to deliver more power output (PO). In the present study this will be further referred to as the ability to make a closed chain (9). For example, a previous study found a positive effect of a closed chain on torque production during isokinetic knee extension and flexion (10). It was found that stabilizing the upper body using strapping and grasping the seat with the hands resulted in a higher torque production than without these interventions. In handcycling, this theory might also be applicable: the ability to (partly) use trunk, pelvic and leg function to push off against the backrest and footrests of the AP-bike during handcycling might increase the PO delivered by the arms. Until now, however, this hypothesis has not been tested in handcycling.

The objective of this study was two-fold. The first objective was to determine the effects of making a closed chain on handcycling performance and physiological responses by comparing the sprint PO and physical strain during submaximal exercise in an AP-bike with footrest (closed chain) with the condition in an AP-bike without a footrest (no closed chain). The second objective was to compare the sprint PO and physical strain obtained in the AP-bike with the ATP-bike. It was hypothesized that athletes would generate a higher sprint PO in the ATP-bike, but also a higher physical strain due to the additional recruitment of trunk muscles in addition to the upper extremity muscles.

MATERIAL AND METHODS

Participants

Ten able-bodied individuals (7 men, mean age 26 years and standard deviation (SD) 7 years, height 1.82 m (SD 0.04), body mass 71 kg (SD 8)) were included in this cross-sectional study. The number of participants was based on previous research in handcycling (11–13). All individuals were healthy and active, but inexperienced in handcycling. Inclusion criteria were: height between 1.75 and 1.90 m and hip width of 36 cm or less to fit in the AP-bike (Top End Force RX, Invacare Top End, Pinellas Park, Florida, USA) and ATP-bike (Top End Force RX, Invacare Top End, Pinellas Park, Florida, USA) (see Fig. 1). Exclusion criteria comprised: active medical treatment at the time of the study, diseases and conditions that would interfere with the study, such as injuries of the upper extremities, fever or cardiac and pulmonary disease, and injuries or conditions that prevent them from making a closed chain movement. Participants had to complete a medical screening questionnaire before starting the test. This study conformed with the Code of Ethics of the World Medical Association and was approved by the ethics committee of the Faculty of Behavioural and Movement Sciences at Vrije Universiteit Amsterdam, the Netherlands. Informed consent was obtained from all individual participants included in the study.

Test protocol

The tests were performed in a laboratory setting with the AP-bike or ATP-bike attached to a cycle ergometer (Cyclus 2, RBM Electronics, Leipzig, Germany). Before the tests started, a familiarization round of several minutes was performed in each bike. A total of 3 different tests were performed on the AP-bike and 1 on the ATP-bike. The tests were scheduled in such a way that no sequence order would appear twice. Participants were randomly assigned to a sequence. The tests on the AP-bike comprised: (*i*) test with foot support of both legs allowing a closed-chain movement, (*ii*) test with foot support of 1 leg to investigate the influence of a partial closed chain on performance, and (*iii*) test performed without foot support to simulate a situation without the ability to perform a closed-chain movement. In the conditions without foot support, the lower leg was attached to a metal frame using elastic banding, which served to keep the legs and feet above the floor preventing any push-off action (Fig. 2). The backrest angle of the AP-bike was between 30° and 45° for all participants and was standardized between tests within a participant.

The test started with a 5-min warm up at a self-selected PO, followed by 2-min rest. After the warm up, 2 4-min submaximal exercise tests were performed at a PO of 30 W and 60 W, based on the study of Hopman et al. (11) and pilot testing. There was a 2-min rest in between exercise tests. During the submaximal exercise tests, oxygen uptake (VO_2) was measured with a Cosmed (Cosmed K4b2 portable system with breath-by-breath analysis, Roma, Italy) and the heart rate (HR) was measured continuously and documented breath-by-breath using a heart rate sensor strap (Polar Electro OY, Kempele, Finland). The mean VO_2 and HR during the last minute of the submaximal exercise tests were used as outcome measures.

After these submaximal exercise tests, there was a 5-min rest, followed by an isokinetic sprint test. In accordance with Zeller et al. (12), the test lasted 20 s, with an initial load of 20 N, with

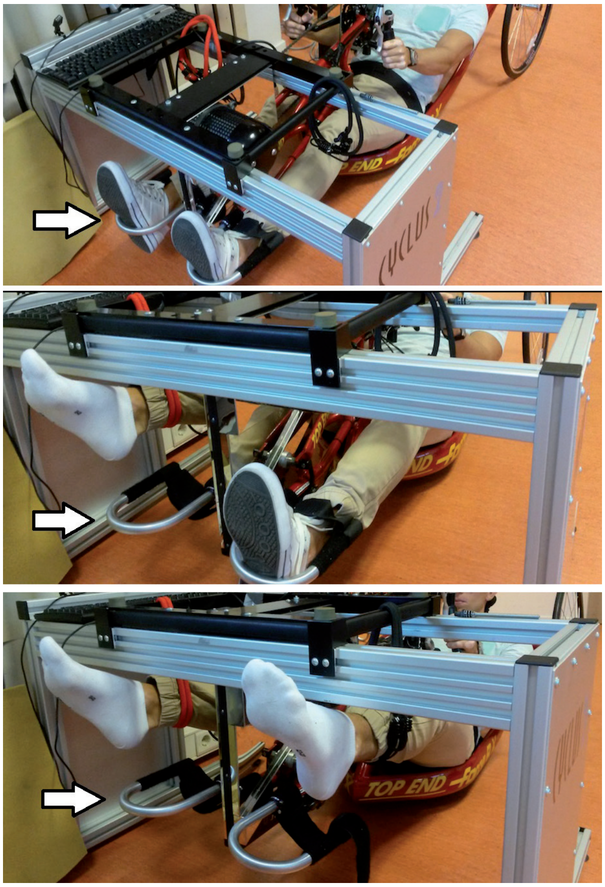

Fig. 2. Two-feet support (*top*), 1-foot support (*middle*), no foot support (*bottom*). *White arrow* indicates the metal frame of the footrests.

a maximum cadence of 110 rpm for the test in the AP-bike and 80 rpm for the test in the ATP-bike. Peak power output (PO_{peak}) was defined as the highest PO and mean power output (PO_{mean}) as the mean PO during the 20-s test.

Statistical analysis

Statistical analysis was performed with SPSS (IBM SPSS Statistics 22). First, the data was tested for normality using the Kolmogorov–Smirnov test with Lilliefors Significance Correction and the Shapiro–Wilk test. In addition, *z*-scores for skewness and kurtosis were calculated. To test the differences between the different AP-bike closed-chain conditions and ATP-bike, a repeated measures analysis of variance (ANOVA) was used. Mauchly's test was used to test the assumption of sphericity. A *post-hoc* Bonferroni test was used for pairwise comparisons. Significance was set at $p<0.05$ for all statistical analyses. Cohen's *d* effect sizes were calculated and were evaluated according to Hopkins (14) as trivial (0–0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), or very large (≥2.00).

RESULTS

Differences in performance when using a closed chain

Both PO_{mean} and PO_{peak} were significantly higher (11% and 25%, respectively) in the AP-bike with 2-feet support compared with the AP-bike without foot support (Fig. 3). The effect sizes were small. There was no significant difference in PO_{mean} and PO_{peak} between the condition with 2-feet support and the condition with 1-foot support. PO_{mean} was significantly higher (10%, $p=0.007$) with 1-foot support compared with no foot support, while PO_{peak} showed a trend towards significance (22%, $p=0.051$). During both submaximal tests (at 30 and 60 W) the VO_2 and HR were not significantly different between the 3 closed-chain conditions (Table I), also shown by the trivial effect sizes.

Arm-Power vs Arm-Trunk-Power

When comparing the AP-conditions with the ATP-bike, both PO_{mean} and PO_{peak} were significantly higher in the ATP-bike (41% and 54%, respectively) compared with

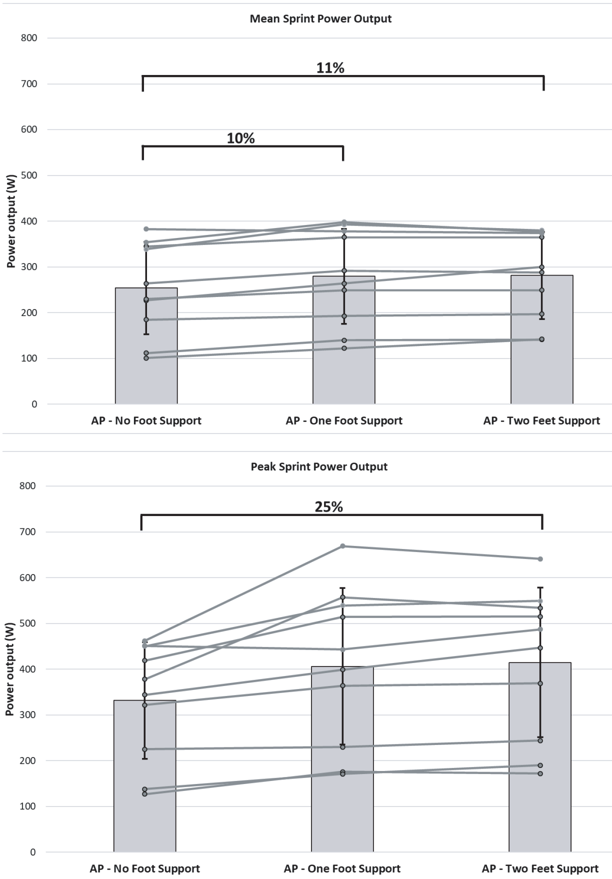

Fig. 3. Mean power output (PO_{mean}) (*upper graph*) and peak power output (PO_{peak}) (*lower graph*) in the different foot support conditions of the Arm-Power (AP)-bike. The percentages indicate the significant improvement in sprint power output between conditions. The lines represent the individual data. For the PO_{mean}, there was a significant difference ($p=0.007$) of 10% between no foot support and 1-foot support and a difference of 11% ($p=0.017$) between no foot support and 2-feet support. For the PO_{peak}, there was a significant difference ($p=0.005$) of 25% between no foot support and 2-feet support.

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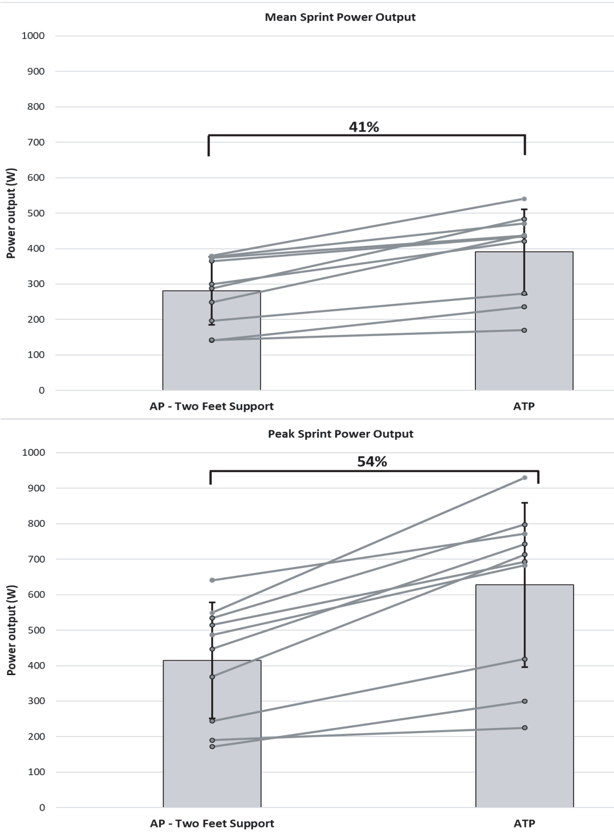

Fig. 4. Mean power output (PO_{mean}) (*upper graph*) and peak power output (PO_{peak}) (*lower graph*) in the Arm-Power (AP)-bike and Arm-Trunk-Power (ATP)-bike. The percentages indicate the improvement in sprint power output between the AP-bike and ATP-bike. The lines represent the individual data. For the PO_{mean}, there was a significant difference ($p=0.001$) of 41% between the AP-bike (2-feet support) and the ATP-bike. For the PO_{peak}, there was a significant difference ($p=0.001$) of 54% between the AP-bike (2-feet support) and the ATP-bike.

the AP-condition with 2-feet support (Fig. 4). Both the VO_2 and HR were significantly higher during the submaximal test in the ATP-bike compared with the conditions in the AP-bike (Table I). The effect sizes for the comparisons between AP and ATP ranged from moderate to very large.

DISCUSSION

The main finding of this study is that in the AP-conditions with foot support a significantly higher PO_{peak} (for 2-feet support) and PO_{mean} (for 2-feet support and 1-foot support) was achieved compared with no foot support during the sprint test. The physical strain was, however, not significantly different between AP-conditions, which was in contradiction to our hypothesis. When comparing the ATP-condition with the AP-condition (2-feet support), the PO_{peak} and PO_{mean} were significantly higher in the ATP-condition. However, higher VO_2 and HR during submaximal handcycling indicated a higher physical strain during handcycling in the ATP-bike compared with in the AP-bike at the same PO.

The ability to make a closed-chain movement seemed to be a great advantage, as the results showed a significant improvement of 11% in PO_{mean} (281 vs 254 W) and 25% in PO_{peak} (415 vs 332 W) in the condition with 2-feet support compared with no foot support and an improvement of 10% in PO_{mean} (279 vs 254 W) in the condition with 1-foot support compared with no foot support. The results of the condition with 2-feet support are in line with the results of a previous study by Zeller et al. (12). That study reported a PO_{mean} between 300 and 400 W and a PO_{peak} between 400 and 500 W during an isokinetic sprint test.

The improvement between the different closed-chain conditions in the present study can be explained by the push-off force against the footrests. When an athlete has the ability to make a closed-chain movement and use this push-off force, he/she can use this for stability (9) and, therefore, generate more power in the AP-bike. The physical strain necessary for this movement was, however, not significantly higher in the condition with 2-feet support. This leads to our hypothesis that, apparently, in the condition without foot support, muscles are activated to the same extent. This muscle activation, however, does not contribute to power output, due to lack of foot support. It is, therefore, expected that handcyclists who are able to make

Table I. Results of the 4 test conditions for the submaximal exercise tests and the sprint test (able-bodied participants $n=10$)

	ATP-bike Mean (SD)	AP: 2-feet support Mean (SD)	AP: 1-leg foot support Mean (SD)	AP: no foot support Mean (SD)	F	*p*-value	ATP-bike vs. AP: 2-feet support *p*-value	Cohen's *d*	AP: 2-feet support vs. AP: no foot support *p*-value	Cohen's *d*
PO_{mean} (W)	391 (121)[a]	281 (96)[a,b]	279 (104)[c]	254 (101)[b,c]	39.75	<0.001	0.001	1.01	0.017	0.27
PO_{peak} (W)	628 (231)[a]	415 (163)[a,b]	406 (171)	332 (127)[b]	40.06	<0.001	0.001	1.07	0.005	0.57
VO_2 30 W submax (ml/min)	967 (132)[a]	703 (86)[a]	693 (37)	709 (91)	33.10	<0.001	<0.001	2.37	1.000	−0.07
VO_2 60 W submax (ml/min)	1,437 (170)[a]	1,110 (130)[a]	1,088 (66)	1,098 (120)	18.41	<0.001	0.007	2.16	1.000	0.10
HR 30 W submax (bpm)	104 (13)[a]	86 (12)[a]	87 (10)	86 (11)	24.41	<0.001	0.002	1.44	1.000	0.00
HR 60 W submax (bpm)	130 (20)[a]	112 (19)[a]	111 (14)	110 (16)	11.19	0.003	0.025	0.92	1.000	0.11

[a]Significant difference between ATP and AP 2-feet support. [b]Significant difference between 2-feet support and no foot support. [c]Significant difference between 1-foot support and no foot support.
PO_{peak}: peak power output; PO_{mean}: mean power output; AP: Arm-Power-bike; ATP: Arm-Trunk-Power-bike; bpm: beats per min; HR: heart rate; SD: standard deviation; VO_2: oxygen uptake; F: F (Fischer)-statistic.

a closed-chain movement will have an advantage. The finding that the AP-condition with 1-leg foot support resulted in significantly higher sprint PO compared with the AP-condition without foot support implies that athletes with, for example, a single-leg amputation would be able to make a closed-chain movement and will therefore have an advantage compared with athletes with, for example, a motor complete spinal cord injury during a race.

Results regarding the comparison of the AP-conditions with the ATP-condition are in line with the results of a previous study in able-bodied participants (13). Verellen et al. (13) studied PO and mechanical efficiency during a graded exercise test and submaximal tests, respectively. PO_{peak} was found to be 10% higher in the ATP-bike compared with the AP-bike. In general, the mechanical efficiency was lower in the ATP-bike, depending on the chosen cadence. An explanation for the higher PO_{peak} is that in the ATP-bike a larger amount of muscle mass is involved, as the trunk and the upper extremities together can generate more power than the upper extremities alone (13, 15). Moreover, gravitational forces can help to generate a more forceful downward movement of the cranks in the ATP-bike (13, 16), resulting in a higher PO. However, because there is no trunk support in the ATP-bike, higher trunk stabilization demands are a plausible explanation for the higher physical strain observed in this type of handcycling (13, 17, 18).

Study limitations

The able-bodied participants in our study were untrained in the AP-bike and ATP-bike. Although a familiarization round was performed, it is expected that, especially the trunk movement technique in the ATP-bike, was not yet optimal in these inexperienced participants compared with handcycling athletes who are used to training on an ATP-bike. Nevertheless, a clear and significant effect was found between the AP-condition and the ATP-condition. It is expected that this effect on PO between the AP-condition and the ATP-condition will be even larger when trained handcyclists participate in the study, as they are skilled in the trunk movement technique. An advantage of able-bodied participants is, however, that the group is homogeneous, that there is no preference in bike-type beforehand, and all participants are physically able to complete all test conditions.

Future studies

Future studies should focus on the comparison of large groups of H4 and H5 athletes using both AP-bikes and ATP-bikes, instead of able-bodied participants, thereby correcting for personal, disability characteristics and training status. Due to the large number of athletes needed, this might be methodologically challenging and might need an internationally collaborative approach. Secondly, additional outcome measures could be investigated. For example, quantification of muscle activity using electromyography (EMG) might be very useful to make clear distinctions between the different abilities to make a closed chain. And force measurements systems applied to the footrests would be very useful to measure the actual force that could be applied to the footrests in the different conditions. Also, lactate measurement after the sprint tests or during graded exercise tests could be helpful to distinguish different physiological responses in the different conditions. Thirdly, in future studies it is important to perform tests mimicking longer races, such as time trials. As the tests in this study were performed in a laboratory setting, air resistance did not play a role. However, air resistance represents more than 90% of the total resistance in handcycling (19, 20). Therefore, one could imagine that during time trials on a flat terrain with a high velocity, athletes in an AP-bike have an advantage compared with athletes in an ATP-bike. However, during sprints or mountain trials (with steep slopes and a low velocity) athletes in ATP-bikes will have an advantage (16).

Implications

The results of this study imply that the PO achieved during a sprint is influenced by the ability to make a closed-chain movement. Following current classification regulations, athletes with impairments that would fit the H5 class, but who are unable to kneel in an ATP-bike, for example because of severe scoliosis, are allowed to ride in an AP-bike and subsequently classified as H4 athletes. Consequently, among the H4 athletes who are mostly unable to make a closed-chain movement, there are few athletes who have the closed-chain ability. As our results showed that the closed-chain ability influences handcycling performance, this should be taken into consideration either in classification or by adding a technical rule preventing footrest use for any push-off action. The consequence would be a fairer competition, as all athletes in the same class will be able to make a closed-chain movement to the same extent.

Conclusion

This study showed that the ability to make a closed-chain movement offers an advantage during handcycling. Therefore, this should be taken into consideration either in classification or by adding a technical rule preventing footrest use. Moreover, the ATP-bike appears to be advantageous during sprints, as was shown by the significantly higher PO. Environmental factors were, however, not taken into account.

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The authors have no conflicts of interest to declare.

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